Three-Dimensional Stratigraphic Complexity Within Mixed Eolian-Fluvial Successions: Implications for Reservoir Connectivity

Oliver Wakefield[1], Nigel Mountney[2], Ed Hough[1], Jo Thompson[1,3]
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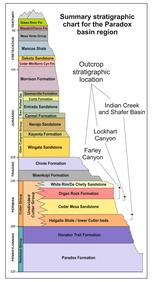
Introduction

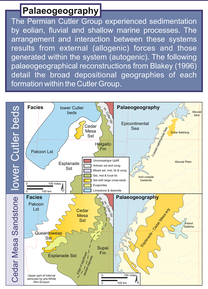
Overview

The Cutler exposed in the Paradox Basin SE Utah, is comprised of sedimentary rocks of eolian, fluvial and shallow marine affinity. The arrangement and relationship of these depositional systems is responsible for a myriad of sedimentary expressions. Whilst reference is made to various parts of the group the lower Cutler beds form the main focus of this poster.



Palaeogeography

The Permian Cutler Group experienced sedimentation by eolian, fluvial and shallow marine processes. The arrangement and interaction between these systems results from external (allogenic) forces and those generated within the system (autogenic). The following palaeogeographical reconstructions from Blakey (1996) detail the broad depositional geographies of each formation within the Cutler Group.


lower Cutler beds
Cedar Mesa Sandstone
Facies
Palaeogeography
Cedar Mesa Sst
Halgaito Sh
Paleozoic Uplift
Epicontinental Sea
Alluvial Plain
Paleozoic Uplift
Paleozoic Uplift
Paleozoic Uplift
Esplanade Sst
Super Fm
Tonsil Sandstone
Tonsil Sandstone
Paleozoic Uplift
Paleozoic Uplift
Paleozoic Uplift

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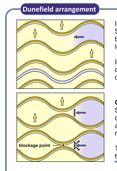
Introduction

Overview

The preserved sedimentary expression within dryland environments was traditionally thought of as the product of either extensive ephemeral fluvial sedimentation or by eolian sedimentation in the form of varying styles of migrating duneforms. However, within the last couple of decades increasing evidence has shown that few dryland environments remain solely within the remit of either eolian or fluvial completely, commonly exhibiting a mix of both. This study details the four types of eolian-fluvial interaction.

Dunefield arrangement

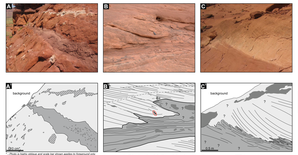


In-phase duneform trains
Sinuous duneforms that maintain equidistant spacing between bedforms in the train. As such, the interdune space is often open and continuous along its length.

In this idealised example, in-phase configuration of the sinuous transverse dunes allows fluvial incursions, as either a pervasive or channelised flow, to occupy and flow along interdune corridors.

Out-of-phase duneform trains
Sinuous crested bedforms with an out-of-phase configuration. The configuration generates areas in the dune train where interdunes narrow, *and dependant upon the dune wavelengths*, become pinched. This relationship creates natural bottle-necks to incursive fluvial flow.

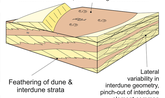
The idealised example here depicts the complete barring of fluvial flow where two duneforms meet.



Rhizoliths and associated concretion
Rip-up clast
Cross-strata
Obstacle / fallen blocks / hollows
Interdune bounding surface
Sand dunes
Interdune
Photo background
Scale indicator

Examples of coeval dune- interdunes with diagrammatic illustrations. Feathering denotes coeval nature, most notable in 'B' & 'C'. Conceptual model below indicates relationship.

Sedimentary structures include desiccation cracks, adhesion structures, root mottling & bioturbation

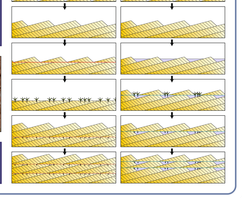


Eolian surface generation

Deflationary Supersurfaces
Generated from periods of sediment supply restriction and/or increase wind carrying capacity. Resulting in a net loss of sediment from the dunefield with duneforms migrating at zero angles of climb (bypass).

Flooding Supersurfaces
Fluvial incursions result in the raising of the activation energy of sediment to wind entrainment - effectively reducing the sediment supply. Duneforms begin to bypass.

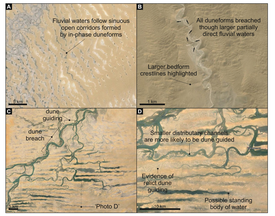
Examples of regional correlatable eolian supersurfaces. In both of the above examples rhizoliths eminate from the supersurface and denote an unconformity, i.e. the time required for colonisation by vegetation.



Interdune Guiding

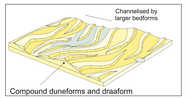
Overview

Interdune guiding results from the incursion of the eolian dunefield by fluvial waters along open interdune corridors. The size of the interdune and dune wavelengths can either limit the incursion into small highly guided corridors or allow more freedom within relatively larger interdune expanses. Interdune guiding as depicted in the modern examples (*situated to the right of this text*) force the fluvial system to flow perpandicular to the prevailing eolian migration direction. As such, instances whereby the fluvial drainage direction and wind direction are near perpendicular to each other facilitates this interaction type. Dune guiding also commonly occurs with close association to examples of eolian dune breach.



Google Earth images of dune/interdune control on fluvial waters (dune guiding). A) Northwest of Lake Chad, Chad; B) Southwest Taklimakan Desert, China, C & D) Central Tombouctou Region, Mali. Note that dune guiding occurs with intermittent examples of dune breach.

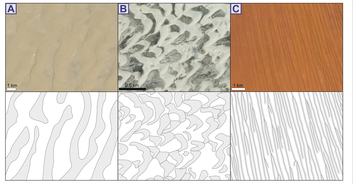
Conceptual model below details the dune guiding effect that larger eolian duneforms or draaforms may exert upon fluvial waters in instances where smaller bedforms are breached and reworked.



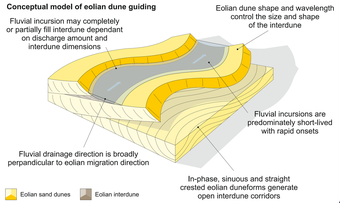
Dunefield arrangement

Modern examples of eolian dunefield configuration. Each example is accompanied by a diagramatic representation of the dune and interdune morphologoes. Note barchan dunes of 'B' and their arrangement generate no continuous interdune corridors, as such, preventing this interaction type.

A) Sinuous-crested highly variable dunes, Taklamakan Desert, China, B) Barchan dunes, Lençóis Maranhenses, Brazil, C) Regular spaced linear dunes, Simpson Desert, Australia.



Conceptual model of eolian dune guiding



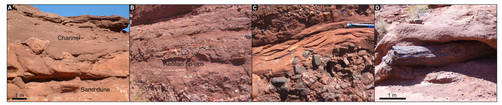
Eolian Dune Breach

Overview

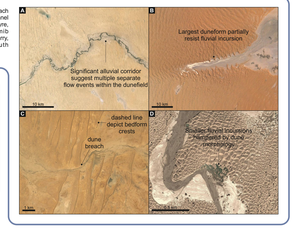
Interdune breach results from the cutting of eolian dunes by fluvial incursions. Such instances usually involve relatively large flood events, whereby the fluvial incursion has the energy to erode and remove barrier dunes. This interaction is best facilitated where competing system flow directions are opposed (180°).

Examples of eolian dune breach by fluvial channel elements. Fluvial channel penetration into the dunefield is restricted to the most energetic channel elements, as a result they often contain features not normally observed in other smaller channel-forms.

Photos: A) Large channel element with highly irregular erosive base cutting into underlying sand dune element, B) Large channel fill succession with cyclic pulses in energy regime denoted by coarser bands, note eolian sand inclusions, C) Close-up example taken from photo 'B', D) Energetic fluvial channel fluvial that includes large tree trunks.

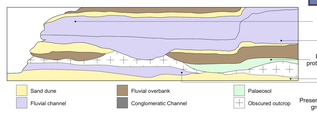


Examples of eolian dune breach as a result of fluvial channel penetration. A) North Lake Eyre, South Australia B) Namib Desert, Namibia, C) Lake Harry, South Australia, D) South Takklimakan Desert, China.

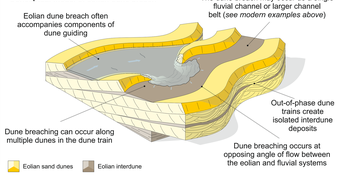


Rock record example

Example from the Undivided Cutler Group, Paradox Basin, SE Utah. In this example eolian sand dune elements are eroded to form two discrete separate lenses. Beyond the limits of the photo the upper and lower sand dune elements meet, suggestive of a coeval relationship.



Conceptual model of eolian dune breach



Interdune Damming

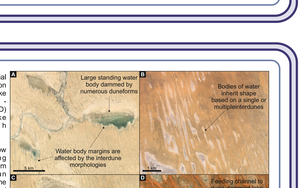
Overview

Interdune damming occurs where flood waters become blocked within the dunefield; a result of three-dimensional, out-of-phase duneform configurations. The damming of the fluvial waters may not be restricted to one interdune, but result from the destruction of some eolian dunes to form a wider dammed area depending on the strength of the fluvial incursion.

Modern Examples

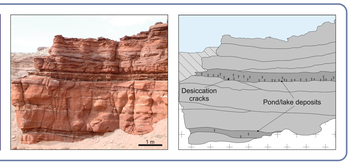
Google earth images of dune damming of fluvial waters. A) Lake Eyre, South Australia, B) Simpson Desert Conservation Park, South Australia, C) Lake Pathraootara - South Australia, D) Northeast Lake Eyre, South Australia.

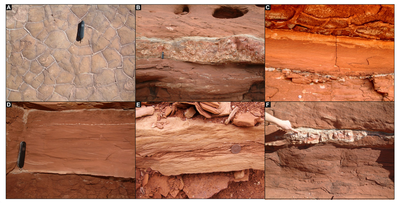
Note 'A' & 'C' show dune damming resulting from multiple eolian duneforms. Some of the dammed lake margins have straight edges resulting from the surrounding duneforms, 'D' depicts a single dam from one interdune element.



Rock record example

The photographic example and diagrammatic interpretation depicts two small sub-metre thick lacustrine deposits. Each shows variable waterlevel indicators through the presence of multiple desiccation cracks emanating from multiple horizons in each element.

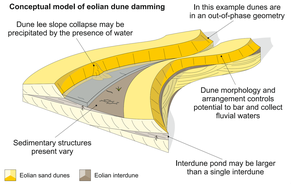




Photographical examples of the potential consistent facies types present within ponded interdune (dammed interdune).

A) Planform example of desiccation cracks, highlighted well by finer, lighter sediment fill to the cracks, B) silcrete layers within an eolian interdune, C) Interdune deposit with small climbing ripples overlain by desiccation cracks, D) Irregular shaped wave ripples, likely resulting from wind agitation, E) well-defined rippleforms, F) smaller thin example of silcrete lens.

Conceptual model of eolian dune damming



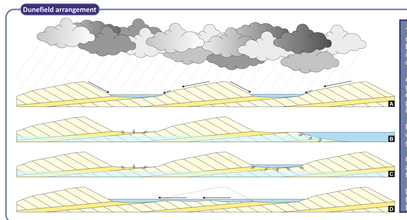
Accessory Flooding

Overview

Accessory flooding, though very similar in expression to dune damming / ponding, is distinct in that it occurs isolated from the direct effects of fluvial incursions. Accessory flooding occurs where isolated interdune depressions fall below the level of the watertable; thus forming isolated ponds. The watertable rise required to form this interaction is not solely within the remit of fluvial incursions and could relate to from; i) fluvial incursions, ii) intra-system precipitation events, or, iii) proximity to larger permanent waterbodies. Importantly as the flooding of the interdune occurs from a watertable source, the deposits will be absent in fluvial facies types - a key diagnostic feature in discriminating between this interaction type and dune damming.

Example facies Photo captions; A & B) wave ripples commonly resulting from wind agitation.

Dunefield arrangement



Accessory Flood types

The diagrammatic cross-sections detailed in this section compare three types of accessory flood and an example of dune breach. In each example the interdune flooding occurs in the interdune situated on the leftside of the diagram which is completely enclosed.

A) Precipitation event within the eolian system. Flood waters are gathered within the localised interdune depressions. Such examples are not frequent due to the general absence of precipitation in arid and semi-arid settings. Accessory flooding in such events would be short-lived.

B) Accessory flooding relating to the proximity to larger bodies of water. This type of accessory flooding is the most likely to generate relatively persistent high watertable.

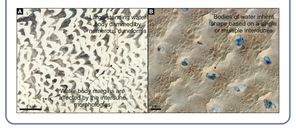
C) Accessory flooding relating to fluvial incursions. Such accessory flooding would be most prevalent adjacent to the flood incursion.

D) Example of dune breach for comparison. Note the removal of the barrier duneform and the chance to preserve fluvial facies types in the adjoining interdunes.

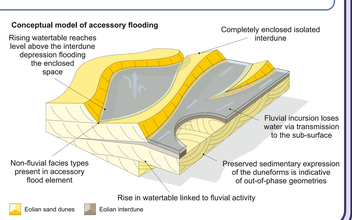
Modern Examples

Google Earth images of accessory flooding within dunefield as a result of watertable rise. A) Lençóis Maranhenses, Brazil, B) South Gobi Desert, Mongolia.

Note that the example from Lençóis Maranhenses experiences accessory flooding in relation to its proximity to the ocean.



Conceptual model of accessory flooding



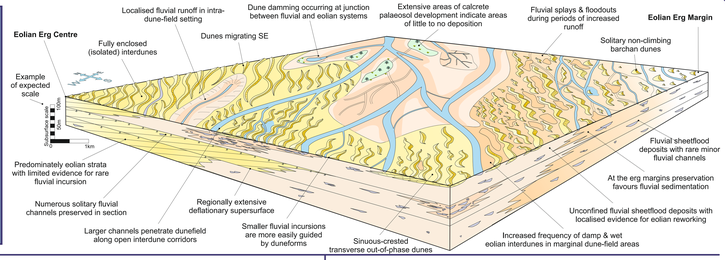
Conclusion

Overview

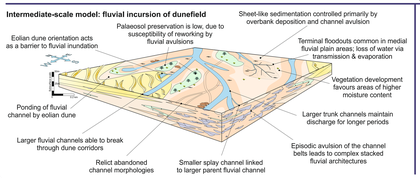
Conceptual model of an eolian dunefield from the erg centre to its margin.

The conceptual model depicts a dunefield subject to varying types of fluvial incursions. Notice the increasing duneform wavelengths, and subsequent interdune geometries, and variation in duneform morphology.

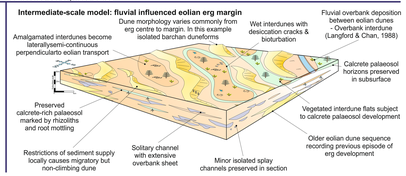
Two higher resolution intermediate-scale models below depict examples of the erg (right to left); i) fluvial incursion of dunefield, and, ii) fluvial influenced eolian erg margin.



Intermediate-scale model: fluvial incursion of dunefield



Intermediate-scale model: fluvial influenced eolian erg margin



Aerial photos taken from Google Earth™

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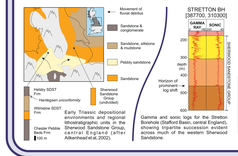
Introduction

Geological setting

The Sherwood Sandstone Group is late Permian to Mid-Triassic (Ladinian) in age. The Early Triassic in Britain was characterised by rifting and extension, related to the break-up of Pangea, with thick accumulations of arenaceous sediments developing in a series of actively subsiding linked half-graben which fringed the local palaeo-high of the Pennines. Locally, preserved sediments reach over 1000 m in some depocentres, with younger units overlapping inter-basinal highs. Regional-scale depositional models suggest a southerly source in the Variscan foldbelt: some few hundreds of kilometres to the south, with northwards draining rivers bifurcated by the Pennine High, diverting sediment westwards towards the Cheshire Basin, Lancashire and Cumbria, and eastwards to the Needwood Basin and East-Midlands Shelf.



Context

The Sherwood Sandstone is a critical geological unit in Britain. It is the 2nd most important groundwater aquifer in England, and is a reservoir to hydrocarbon fields both onshore and offshore. Its close spatial relationship with the Coal Measures and proximity to major urban areas including Birmingham and Manchester has led to localised contamination. As such, an understanding of petrophysical properties of the group is relevant to many disciplines.

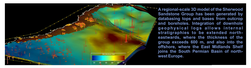
Lithostratigraphy Challenge

The classification of the Sherwood Sandstone is largely based on lithostratigraphy, due to an absence of age-diagnostic fossils. Historically, this succession has been split by using gross differences in composition and character (e.g. pebble content, degree of cementation). However, whilst this approach is successful in areas of lithological variability and good outcrop exposure, and can to some extent be confirmed by borehole cores and logs, it is difficult to apply where variations are more subtle, or outcrop and cores are not available.

The Sherwood Sandstone Group exhibits considerable facies variation to the west of the Pennines (Cheshire and East Irish Sea basins). In many areas, the group can be divided into a tripartite succession comprising a lower fluviatile unit, a middle unit that is predominantly eolian (becoming more so in distal areas), and an upper unit of mixed eolian and fluvial facies which have a complex spatial relationship. In this succession, major erosive bounding surfaces may represent significant time-gaps. Whilst this subdivision is possible across much of central and north-west England, correlations in the north-east (East Midlands Shelf and Cleveland Basin) are difficult to establish and the group remains undivided in the east.

Last vs West

To the east of the Pennines, the apparent lack of local and regional-scale lithological variability in a sandstone-dominated succession that reaches over 600 m in thickness is difficult to explain given the obvious variability at the outcrop-scale, where a degree of emergence (overbank and the development of rare vertisols) is evident at outcrop. The relationship between basins to the east and west of the Pennines hinges on a key region between the Needwood Basin and East Midlands Shelf. Bedrock exposure is poor, and there is an absence of borehole core material to analyse, precluding a fuller understanding of this relationship.



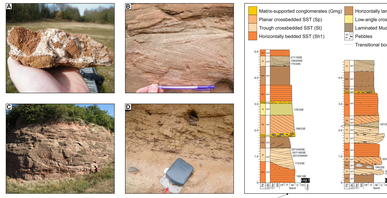
Adding detail to models

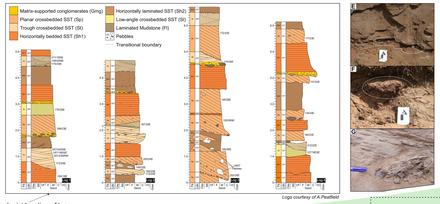
Analysis of outcrop sections from the East Midlands Shelf show a variable facies and element constituent at the sub-seismic (up to ~5 m) scale. This is not observed on down-hole or traditional lithological logs, and facies analysis is much improved by integrating borehole descriptions with log. One important marker horizon that can be identified from geophysical logs to the west of the Pennines is a prominent log shift within the lower part of the Sherwood Sandstone. This is characterised by an upward decrease in both sonic and gamma responses, and although identified regionally and offshore into the East Irish Sea Basin (e.g., Colter & Barr, 1975), the interval has not been described from cores onshore. However, it is likely that the interval represents an upward-drying event, with facies becoming less clay-prone.

Architectural Panel

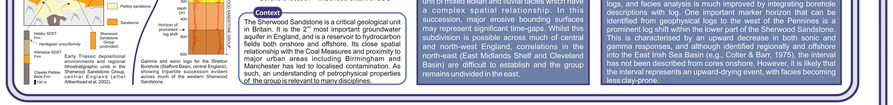
Code	Lithology	Sedimentary structure	Interpretation
Sgb	Sand, medium- to coarse grained, with abundant pebbles (>20% by vol.)	Normally graded – sometimes weakly (A)	Channel lag deposits
Sp	Sand, medium- to coarse grained, sometimes pebbly	Planar crossbeds arranged in single or multiple sets (B)	Migration of single / multiple 2D bedforms
St	Sand, medium- to coarse grained, sometimes pebbly	Trough crossbeds arranged in single or multiple sets (B)	Migration of single / multiple 3D bedforms
Sl	Sand, fine - to coarse-grained, isolated pebbles	Low-angle crossbedding = <15° (C)	Migration of humpback dunefoms (cf. Kostaschuk and Villard, 1996)
Sh1	Sand, medium- to coarse-grained, isolated pebbles	Horizontal bedding/lamination, parting lineation (D)	Upper plane beds (upper flow regime)
Sh2	Sand, very-fine- to fine-medium-grained	Horizontal lamination, rare instance of cm scale bedding (E)	Migration of ripplefoms
Sr	Sand, fine-to-medium-grained	Ripple cross-lamination (G)	Migration of ripplefoms
Sm	Sand, fine- to coarse-grained, isolated pebbles	Structureless - Massive (F)	Gravity flow deposit
Fl	Silty sand (very fine) rare instances of mud	Fine lamination, often contains crude ripplefoms (H)	Non-channelised flow and settling from suspension

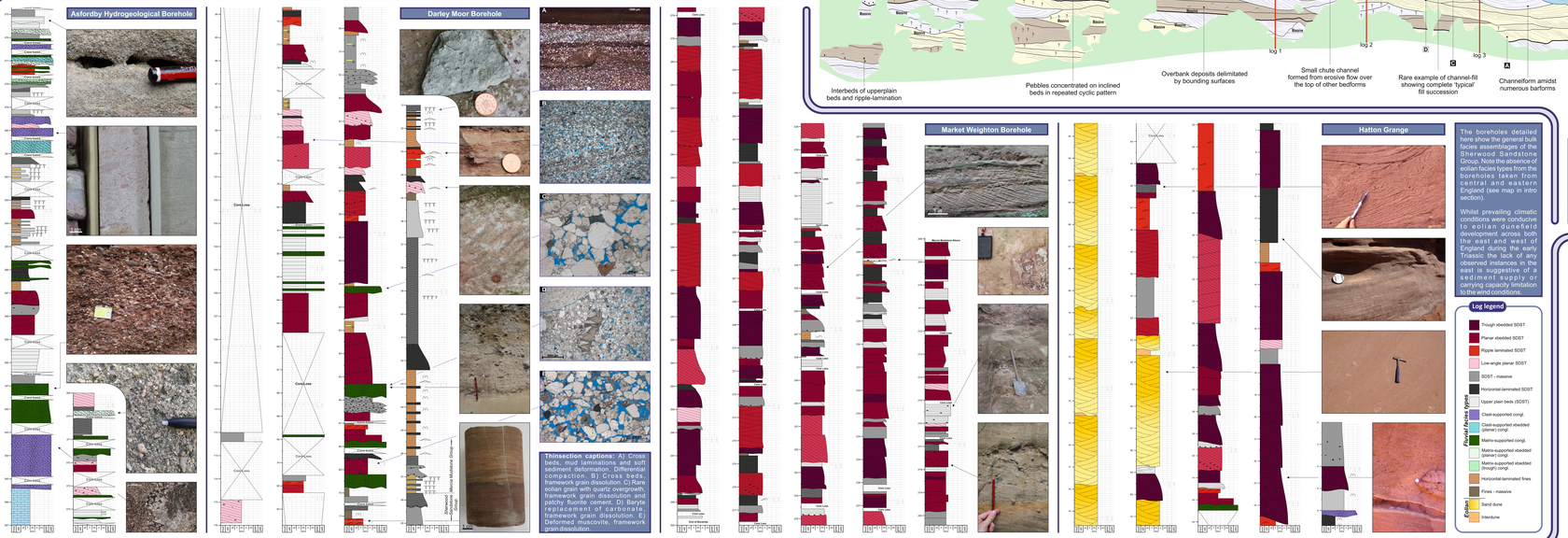
Name	Description
Lateral accretion element	Lensoidal shaped with a lateral extent of 10-18m and thicknesses 1 - 2 m.
Channel	Erosively based 'u' shaped element. Lateral extents of up to 20 m and thicknesses up to 3 m.
Downstream accreting element	Lensoidal shaped, <2.6 m thick with lateral extents up to 40 m.
Chute channel	Smaller erosively based channel feature; 1 2 - 2.6 m wide with a thickness ~0.5 m.
Sandy floodplain	Discontinuous tabular shape, thicknesses up to 3 m and lateral extents of up to 20 m.





Logs courtesy of A.Pickford




Asfordby Hydrogeological Borehole
Darley Moor Borehole
Market Weighton Borehole
Hatton Grange
Cornbrash
Corallian
Oxford Clay
Kellaways Beds
Cornbrash Fm.
Forest Marble Fm.
Great Oolite Group
Corallian Group
Oxford Clay Fm.
Kellaways Beds Fm.
Kimmeridge Clay Fm.
Ampthill Clay Fm.
Lower Oxford Clay
Kellaways Sand Mbr.
Kellaways Clay Mbr.
Cornbrash Fm.
Forest Marble Fm.
Great Oolite Group
Corallian Group
Oxford Clay Fm.
Kellaways Beds Fm.
Kimmeridge Clay Fm.
Ampthill Clay Fm.
Lower Oxford Clay
Kellaways Sand Mbr.
Kellaways Clay Mbr.
Sherwood Sandstone Group
Mercia Mudstone Group
Penarth Group
Blue Anchor Fm.
Lilstock Fm.
Westbury Fm.
Cotham Mbr.
Langport Mbr.
Lilstock Fm.
Blue Anchor Fm.
Mercia Mudstone Group
Sherwood Sandstone Group
Penarth Group